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AERODYNAMIC HEATING AND ABLATION COMPUTER PROGRAM (HEATAB)

William J. Moulds

J. D. Young
Lt USAF

TECHNICAL REPORT NO. AFWL-TR-66-105

October 1966

AIR FORCE WEAPONS LABORATORY
Research and Technology Division
Air Force Systems Command
Kirtland Air Force Base
New Mexico

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FOREWORD

This report was prepared under Project 627A, Program Element 6.44.06.12.4, Weapon System 627A.

Inclusive dates of research were January 1966 through May 1966. This report was submitted by the authors 18 August 1966.

The authors wish to thank Mrs. Barbara G. Deimer and Jerome L. Hitchcock for their assistance in the preparation of this program and report.

This report has been reviewed and is approved.

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ABSTRACT

An Aerodynamic Heating and Ablation Computer Program (HEATAB) is presented to establish a means by which heat transfer problems may be solved with minimum effort. This program computes the boundary layer conditions, time-temperature distribution in a body, the ablation recession rate, and weight loss. The program was written in Fortran IV for the CDC 6600 computer.

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CONTENTS

ILLUSTRATIONS

SECTION I

INTRODUCTION

This program is an outgrowth of a need for aerodynamic heating and ablation analysis of hypersonic reentry vehicles. The present design requirements for advanced systems of high performance reentry vehicles have resulted in a severe thermal environment around the nose and conical surfaces of the vehicles. The most popular, self-regulating type of heat protection system, the ablating heat shield, will produce a surface erosion and nose blunting. Large shape changes, which will influence the aerodynamic performance of the vehicle during flight, may be produced. This vehicle shape change for an ablation-type system is important from a systems standpoint in determining the actual performance of the vehicle during flight. Equally important from a systems standpoint is the determination of boundary-layer parameters for R-F transmission as well as temperature-time profiles in the vehicle for temperature-sensitive instruments.

It is our hope that this report will help the nonthermodynamicist understand his problem and solve it with minimum effort. The equations of heat transfer are general in that they apply to most axially symmetric vehicles of any composite skin structure. The vehicle skin is assumed to be made of discrete layers of material whose properties may vary from layer to layer. The existing computer program is specific in that the equations have been applied to a sharp-nosed, conical vehicle. With a thorough understanding of thermodynamic principles, as applied to a conical vehicle, and with a basic knowledge of computer programming, the reader should be able to adapt this program to any vehicle.

SECTION II

BACKGROUND AND THEORY

1. Background

Advances in hypersonic atmospheric flight have resulted in environments of extremely high temperatures. Boundary layer temperatures in excess of 10,000°F are characteristic of vehicles entering the atmosphere at hypersonic speeds. As a result, the thermal barrier is at present the major obstacle to the safe reentry of vehicles. The term "thermal barrier" refers primarily to the problems associated with the dissipation of the vehicle energy to the surrounding air. For sharp bodies at hypersonic speeds, most of the dissipation occurs in the boundary layer. The viscous stresses within the boundary layer exert shearing work on the fluid and raise its temperature appreciably. This work, called aerodynamic heating, also raises the surface temperatures of bodies within this environment.

In hypersonic flight, it becomes obvious that capacitance or mass heat sink protection, though simple, is an impossible means of coping with the extremely high total heat input associated with hypervelocity reentry vehicles. Consequently, other means of cooling or protecting for operating beyond heat sink limitations must be used. One convenient means for meeting this form of environmental protection is by the method of ablation cooling.

The ablative process is illustrated in figure 1. The ablation process works in the following manner: (1) the material or ablator acts as a heat sink, (2) when the critical or melting temperature of the ablator is reached, a thin layer of the material at the surface will begin successively to melt, vaporize, depolymerize, or decompose chemically, (3) as the material vaporizes, the gaseous products of decomposition enter into the boundary layer. Being relatively cool, as compared to the boundary-layer air, the injected gas forms a thin but effective film that greatly reduces the heat transfer to the vehicle surface.

Experiments have verified that, in high-speed flow, the magnitude and direction of heat flow at the surface does not depend on the difference between the wall temperature and the free-stream temperature as in low-speed flow, but

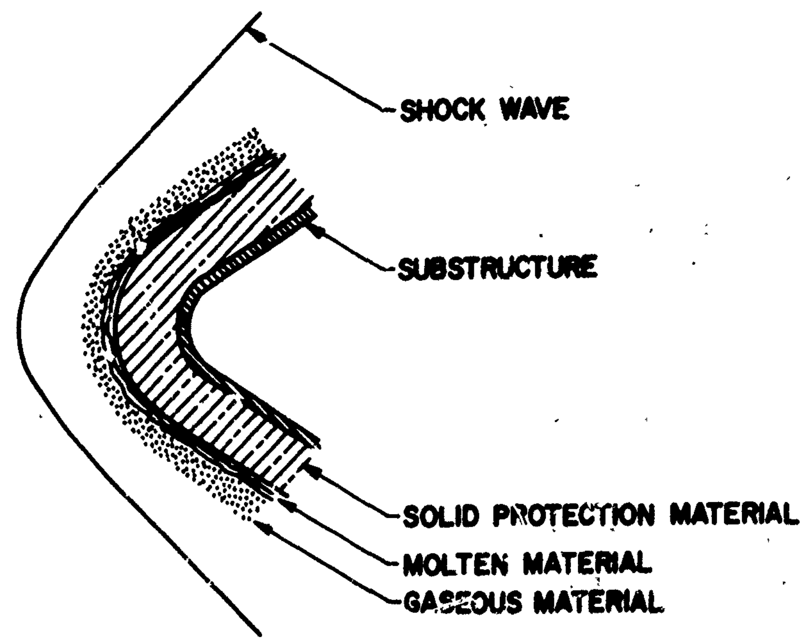

Figure 1. Ablative Process

rather on the difference between the wall temperature and the adiabatic wall temperature. To correlate experimental data, it is convenient to define the unit surface heat rate (reference 1) for high-speed flow as

$$\dot{q}_c/A = \bar{h}e\ (TAW - TW)$$

where

$\dot{q}_c/A$ = heating rate BTU/sec - ft^2

$\bar{h}e$ = convective heat transfer coefficient -BTU/ft^2 - sec - °R

TAW = adiabatic wall temperature - °R

TW = vehicle wall temperature - °R

A = local wetted area - ft^2

It is important in the selection of a suitable material for thermal protection by the ablative process that the products of decomposition have a high specific heat. This in turn produces a high effective mean specific heat of the gas-air mixture in the boundary layer and a high Prandtl number. It is also desirable that the ablator have a low thermal conductivity. This will decrease heat conducted to the interior of the vehicle.

2. Heat Transfer Coefficient

In conventional analysis of heat transfer by forced convection, the nature of the flow can be described by the Reynolds number, which is a dimensionless measure of the ratio of inertial to viscous forces. In high speed flow, at least two additional parameters must be considered. These are Mach number and Prandtl number. The parameter Mach number (AMACH) describes the influence of compressibility on heat transfer and flow phenomena and is defined as the ratio of the gas or flight velocity VEL to the local or ambient speed of sound VS. The Prandtl number, Pr, is defined as the ratio of heat storage to heat conduction of a gas.

The heat transfer coefficient (reference 2) is related to the flow properties through the relation

$$Nu(Pr)^{-1/3} = C(Re)^{a}$$

where

Nu = Nusselt number = $he\ x/K$

he = effective heat transfer coefficient

X = distance from the nose - ft

k = thermal conductivity of air - BTU/ft - sec - °R

Pr = Prandtl number = $C_p \mu/K$

C_p = specific heat of air - BTU/lb - °R

μ = viscosity of air - lb - sec/ft^2

Re = Reynolds number = $\rho Vx/\mu$

ρ = density of air - lb - sec^2/ft^4

V = Boundary-layer edge velocity - ft/sec

C = 0.0296 for turbulent flow (reference 1)
0.354 for laminar flow

a = 0.8 for turbulent flow (reference 1)
0.5 for laminar flow

Good correlation with experimental data is obtained if the gas properties are evaluated at the reference temperature and the velocity is taken as the boundary-layer edge velocity. For the case of mass addition, the properties of the injected gas are used to compute the Prandtl number and Nusselt number.

3. Unsteady Heat Conduction

This section presents a means of applying the Schmidt graphical method for solving an unsteady heat conduction problem. A thorough discussion of this method can be found in any general text on heat transfer (references 1 and 3) and will not be attempted here. This method is quite flexible and difficult boundary conditions can be handled easily.

The graphical method is widely used in industry because it gives a running picture of the changing temperature distribution; its details can be delegated to relatively untrained personnel, and mistakes, if they occur, are quickly discovered. However, for precise computations, especially when variations of physical properties of material with temperature are important, as in the ablation process, a numerical method should be used instead of a graphical method. Numerical methods are especially convenient when a computer is available, since the steps involved in a numerical solution can be programmed without difficulty.

The numerical method for solving unsteady-state conduction problems differs from that used to solve steady-state problems. In the latter cases, the temperature distribution in a body can be obtained for a network of points in a solid by solving a system of residual equations. In unsteady-state systems, the initial temperature distribution is known, but its variation with time must be determined. It is, therefore, necessary to deduce the temperature distribution at some future time from a given distribution at an earlier time.

To illustrate the numerical method, it is first necessary to transform the Fourier conduction equation (a partial differential equation that is second order in space and first order in time) for the unsteady temperature distribution in a heat-conducting solid into a finite difference form.

$$\frac{\Delta_\tau T}{\Delta\tau} = \alpha\frac{\Delta^2_x T}{(\Delta x)^2}$$

the subscript denotes the differentiation variable. Letting n denote position and K time, $\Delta_\tau T$ can be written as

$$\Delta_\tau T = T_{n,k+1} - T_{n,k}$$

In a similar manner

$$\Delta_x T = T_{n+1,k} - T_{n,k}$$

The expression $\Delta_x{}^2 T$ thus becomes

$$\Delta_x{}^2 T = T_{n+1,k} - 2T_{n,k} + T_{n-1,k}$$

Substituting these expressions into the Fourier equation gives

$$T_{n,k+1} - T_{n,k} = \frac{\alpha\Delta\tau}{(\Delta x)^2}\left(T_{n+1,k} - 2T_{n,k} + T_{n-1,k}\right)$$

The temperature throughout a wall or slab can now be computed for any later time if the initial distribution is known. A Schmidt plot demonstrates the temperature profile versus time in a semi-infinite slab (figure 2).

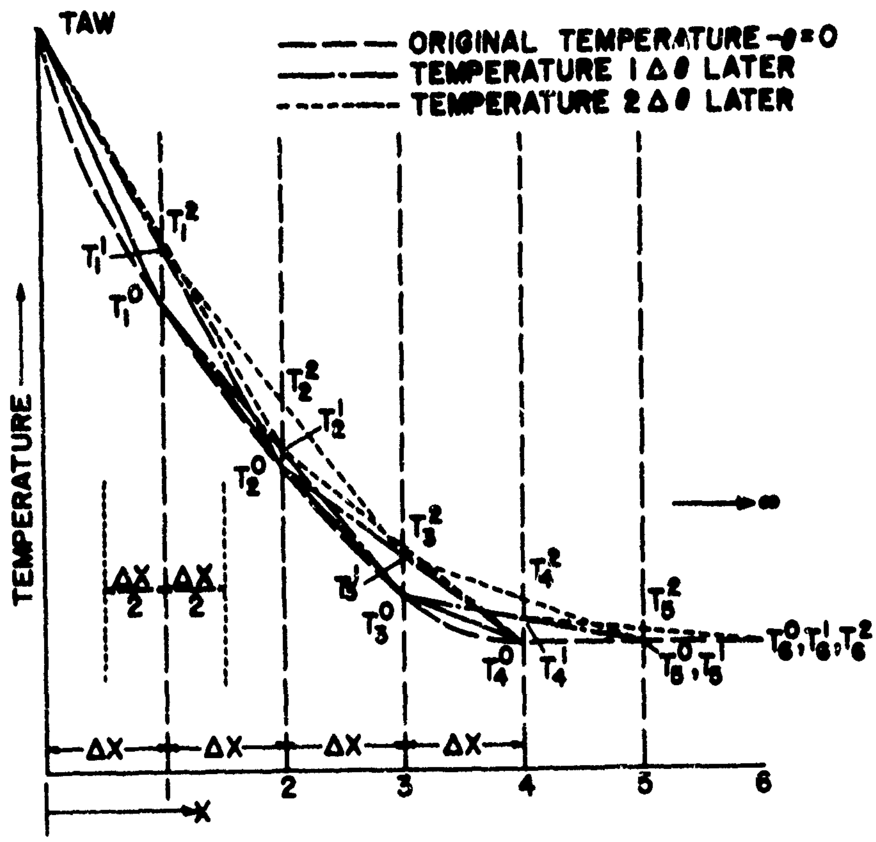

Figure 2. Schmidt Plot in an Infinitely Thick Wall

A constant wall temperature is assumed in the graphical example but a varying wall temperature can be handled with equal ease. By letting the wall temperature vary with time, the distribution at each point within the body can be computed for each time increment.

4. Vehicle Thermal Model

To determine the time-temperature profile in the vehicle skin, the Fourier conduction equation was written as a finite difference equation and solved numerically. This method is a further adaptation of the Schmidt graphical method (reference 3). The wall is divided into a number of lamina with known thickness, specific heat, and thermal conductivity and with a known initial temperature distribution. Figure 3 illustrates the model with its associated nomenclature.

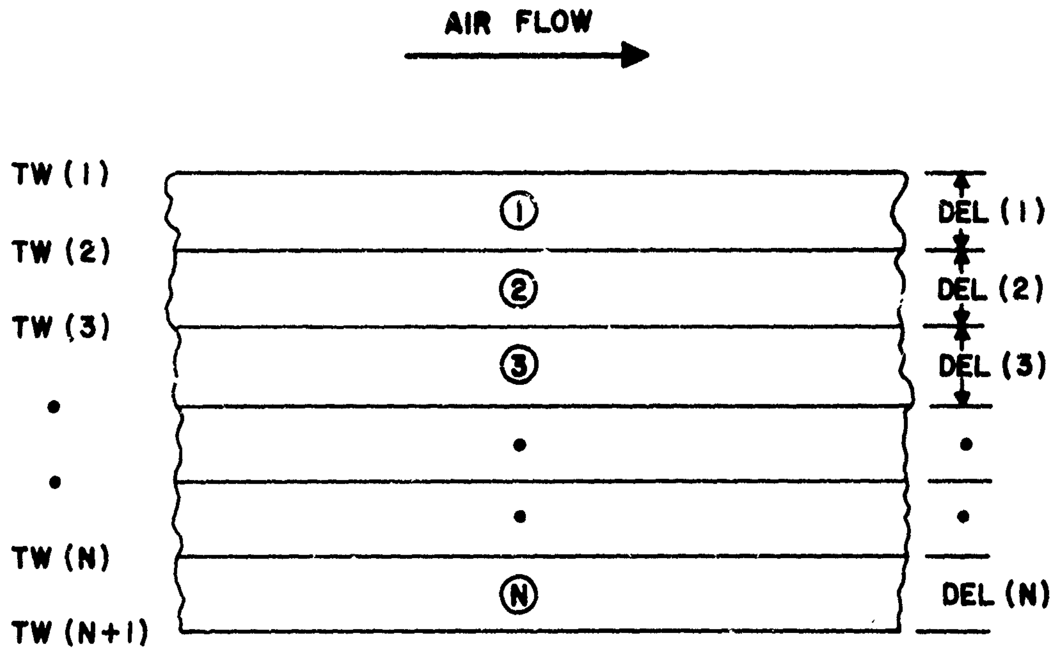

Figure 3. Model for Wall Temperature Profile and Ablation Recession Calculations

The difference equation to compute the temperature at position n at time k+1 is

$$T_{n,k+1} = T_{n,k} + \frac{\alpha\Delta\tau}{(\Delta x)^2}\left(T_{n+1,k} - 2T_{n,k} + T_{n-1,k}\right)$$

In this form, the properties cannot vary from layer to layer. If the properties vary from layer to layer, the above equation must be written in the form

$$T_{n,k+1} = T_{n,k} + \Delta\tau \left[\frac{\alpha_{n-1}}{\left(\Delta X_{n-1}\right)^2} \left(T_{n-1,k} - T_{n,k}\right) - \frac{\alpha_n}{\left(\Delta X_n\right)^2} \left(T_{n,k} - T_{n+1,k}\right) \right]$$

It is useful to replace the thermal diffusivity by its defined equivalent

$$\alpha = \frac{K}{\rho C_p}$$

This step allows one to easily recognize certain groups of terms as the heat conducted through each lamina and permits the convective heat flux to be used in solving for the wall temperature. The equation for the wall temperature is

$$T_{n-1,k+1} = T_{n-1,k} + \frac{\Delta\tau}{\left(\rho C_p \Delta X\right)_{n-1}} \left[he\left(TAW - T_{n-1,k}\right) \right]$$

$$- \frac{\Delta\tau K_{n-1}}{\left(\rho C_p \Delta X^2\right)_{n-1}} \left(T_{n-1,k} - T_{n,k}\right)$$

The backface boundary condition can be specified in several ways. If internal heating (or cooling) is present, the backface temperature may be held constant or allowed to vary in a specified manner. A conservative assumption is that no heat flows through the last lamina. This assumption will cause somewhat more ablation and higher temperatures than would be encountered with a cooled backface or other heat sink material.

5. Mass Loss and Surface Recession

Two mechanisms are involved in the loss of ablation material. These mechanisms are: (1) mass loss due to oxidation, and (2) mass loss due to sublimation. The oxidation is controlled by the diffusion of oxygen to the reacting carbon and the sublimation is controlled by local pressure and temperature. A detailed discussion of the theory of ablation material and decomposition of reaction is not the intent of this report, so only the results will be presented. For a more detailed discussion, see references 4 and 5.

For laminar flow, the diffusion mass loss rate is given by

$$\dot{M}_D = \frac{\dot{q}_c + \dot{q}_{HGR}}{K1_L + K2_L\left(hr - C_{p_{BL}} TW\right)}$$

and for turbulent flow, the equation is

$$\dot{M}_D = \frac{\dot{q}_c + \dot{q}_{HGR}}{K1_T + K2_T\left(h_r - C_{p_{BL}} TW\right)}$$

where the constants K1 and K2 can be interpreted as the intercept and slope respectively on an effective heat of ablation versus enthalpy difference (between recovery and wall conditions) plot.

$\dot{q}_c$ = heat rate - BTU/ft^2 - sec

$\dot{q}_{HGR}$ = heat rate for hot gas radiation - BTU/ft^2 - sec

h_r = recovery enthalpy in boundary layer - BTU/lb

$C_{p_{BL}}$ = specific heat in boundary layer - BTU/lb - °R

TW = wall temperature - °R

$$\dot{q}_{HGR} = \sigma\left(\left(T_{GAS}\right)^4 GE - (TW)^4 ALPG\right)$$

where

σ = Stephan-Boltzmann constant, 4.8×10^{-13} BTU/sec-ft^2 - °R^4

T_{GAS} = gas temperature - °R

GE = gas emissivity at temperature T_{GAS}

TW = wall temperature - °R

ALPG = absorptivity of gas at temperature TW

The total mass loss rate is given by

$$\dot{M}_T = \dot{M}_D \left[1 + 2.64 \times 10^4 (PBL)^{-0.67} \exp\left(- \frac{11.05 \times 10^4}{TW} \right) \right]$$

where

PBL = boundary-layer edge pressure - lbs/ft^2 (reference 6)

The surface recession rate is calculated by

$$\dot{S} = \dot{M}_T/\rho$$

where ρ is the ablation material virgin density. To determine the total recession, $\dot{S}$ is summed after each calculation for a new trajectory point.

6. Calculation of Total Weight Loss Rate

After the local instantaneous and total recession rates have been computed, the local weight loss rate is calculated by determining the volume reduction of the body and multiplying by the material density. It is assumed in this calculation that the recession is uniform over the region of interest. Total weight loss rate is obtained by summing the local rates.

SECTION III

PROGRAM DESCRIPTION

1. Introduction

This section discusses ana esents the basic program (HEATAB) with stagnation point modification (STAGG) for a sharp-nose, conical vehicle. The program was written in FORTRAN IV for the CDC 6600 computer. Only a general flow chart is given. The flow within individual blocks is easily followed from the program listing (Appendixes I and II).

2. HEATAB Description

The basic sequence of calculations is shown on the flow chart of HEATAB, figure 4. After entry into the program, the first steps are the reading of input data and the defining of constants. Descriptive initial conditions are printed to identify the case being run.

Time is the independent variable and its computation marks the entry to the computational loop of the program. The flight conditions, atmospheric properties, and layer index are now determined. A number of methods can be used to input the flight trajectory such as subroutine, punched card, or magnetic tape. The atmospheric properties are computed by subroutines. K is a subscript that indicates the layer for which computation is being performed. The initial value for K is 1. IND(K) is used to indicate to the computer to use virgin or char properties. If T(K) is less than the char temperature, IND(K) will route the computer to virgin material physical properties. Similarly, if T(K) is greater than the char temperature, then char properties will be computed.

The next sequence of calculations determines the recovery temperature, boundary-layer edge conditions, and Reynolds number. Following these calculations, it is determined if ablation is occurring or has occurred. Based on this determination, the correct Prandtl number is computed. Based on the outcome of the decision regarding the existence of turbulent flow, the appropriate recovery factor, heat transfer coefficient, dynamic temperature, adiabatic wall temperature, and gas temperature are calculated. The resulting output of this sequence is the heat flux to the body.

Computing the wall temperature distribution is the function of the next sequence of computations. Again the decision regarding charring and ablating is made and the appropriate physical properties are selected. The temperature TW(1) is computed as a function of the adiabatic wall temperature and TW(2). The temperatures below the surface are next computed as functions of the old adjacent temperatures.

If the wall is ablating, mass is being lost from the vehicle and the wall will recede. The mass loss rate is computed in this sequence, along with the recession rate and new layer thickness. The new thickness is used the next time the temperature calculations are made. The printing of output data marks the completion of one cycle of computation. As a new cycle is started, a decision is made based on the vehicle's altitude. If the altitude for the new time is positive, computation continues; if the altitude is negative, a normal exit is made and computation ends.

3. STAGG Description

This section contains a description of the STAGG version of the aerodynamic heating and ablation program. STAGG is a modification of the basic program that can be used to calculate heat transfer rates on the stagnation point of sharp-nosed vehicles. Heat transfer rates and temperature profiles are calculated by the existing HEATAB equations, using local properties, but the constant in the heat transfer coefficient and Reynolds number for transition from laminar to turbulent flow has been redefined. The constants as defined by Lees' theory (reference 7) and Blausius' skin friction coefficient for point cone heat flux are

C = 0.778 for laminar flow
0.0348 for turbulent flow

Another difference between HEATAB and STAGG is the addition of nose blunting equations.

In the determination of nose blunting, it is assumed that the initial nose shape of particular interest, for which STAGG was written, was a sphere-cone and, after ablation, the final shape was a sphere-cone. Experimental evidence has shown that the final eroded shape could be approximated by a sphere-cone having a small deviation from a sphere. The reference sphere-cone configuration after erosion is obtained by placing a spherical surface tangent to a cone parallel to the original surface but displaced by the erosion on the cone and

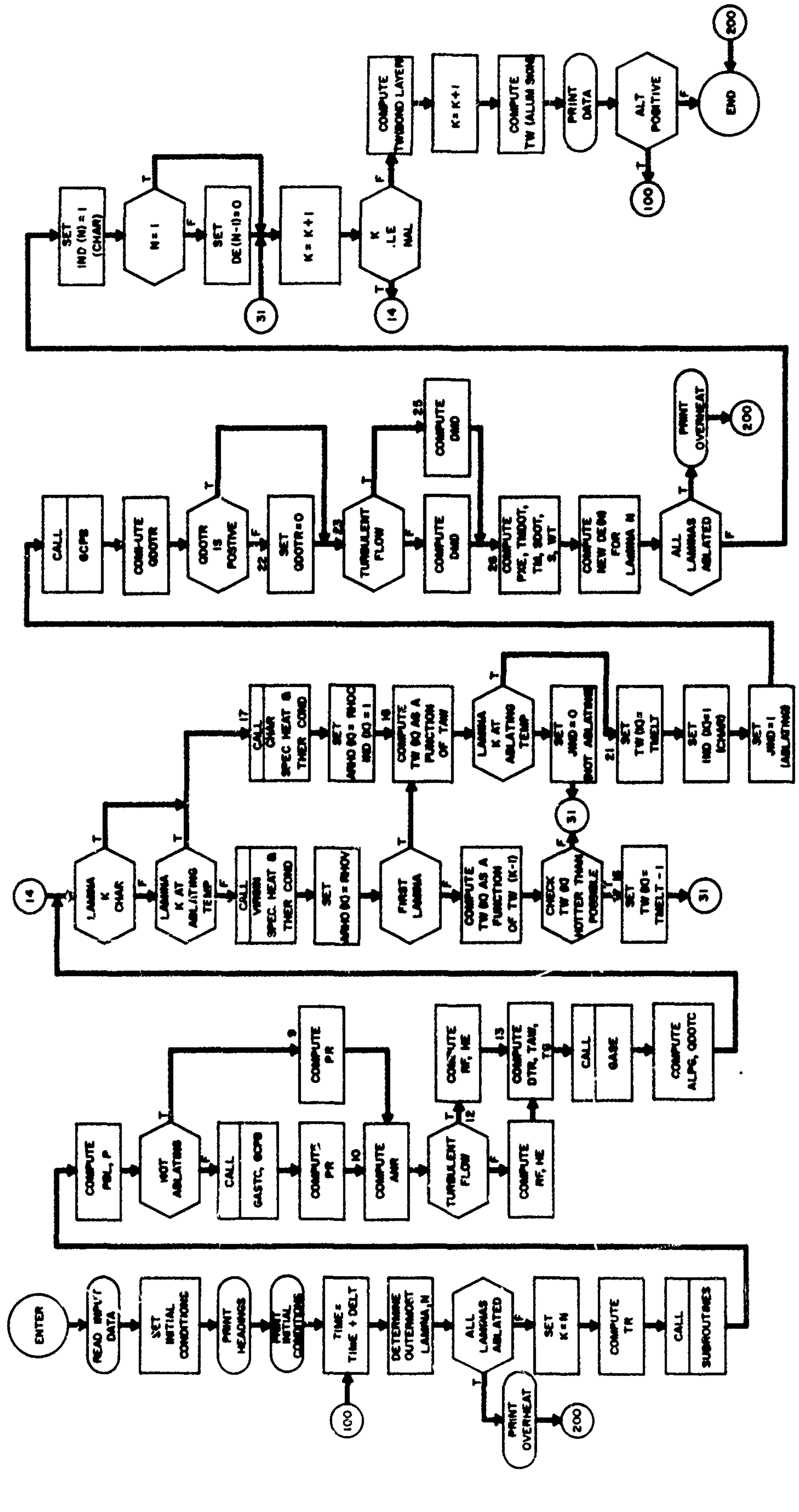

Figure 4. HEATAB Flow Chart

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and located axially at a position on the vehicle center line in accordance with the erosion at the stagnation point. (See figure 5.)

The experimental evidence of nose-shape change of reentry vehicles, as previously noted, can be represented by a sphere-cone shape which deviates from a spherical shape by an amount less than 10 percent of the final nose radius. The final eroded nose radius at zero angle of attack, therefore, can be obtained in terms of the stagnation point erosion and cone erosion as shown in equation

$$R = R_o + \frac{1}{(1-\sin\theta_c)}\left[\sin\theta_c \int_o^{t} \left(\frac{\dot{q}_c}{h_e}\right)_s dt - \int_o^{t} \left(\frac{\dot{q}_c}{h_e}\right)_c dt\right]$$

The integral represents the erosion at a given time during a flight for the locations at the stagnation point (S) and a point on the cone (C) at a location of wetted length of about five times the nose radius.

It is now possible to evaluate the final nose radius for a given application.

Let

$$TDOT = \int_o^t \left(\frac{\dot{q}_c}{\rho he}\right)_s dt$$

$$CDOT = \int_o^t \left(\frac{\dot{q}_c}{\rho he}\right)_c dt$$

$$\therefore R = R_o + \frac{1}{(1-\sin\theta_c)}\left[\sin\theta_c \; TDOT - CDOT\right]$$

where

R_o = original nose radius - ft

R = instantaneous nose radius - ft

θ_c = cone half-angle - radians

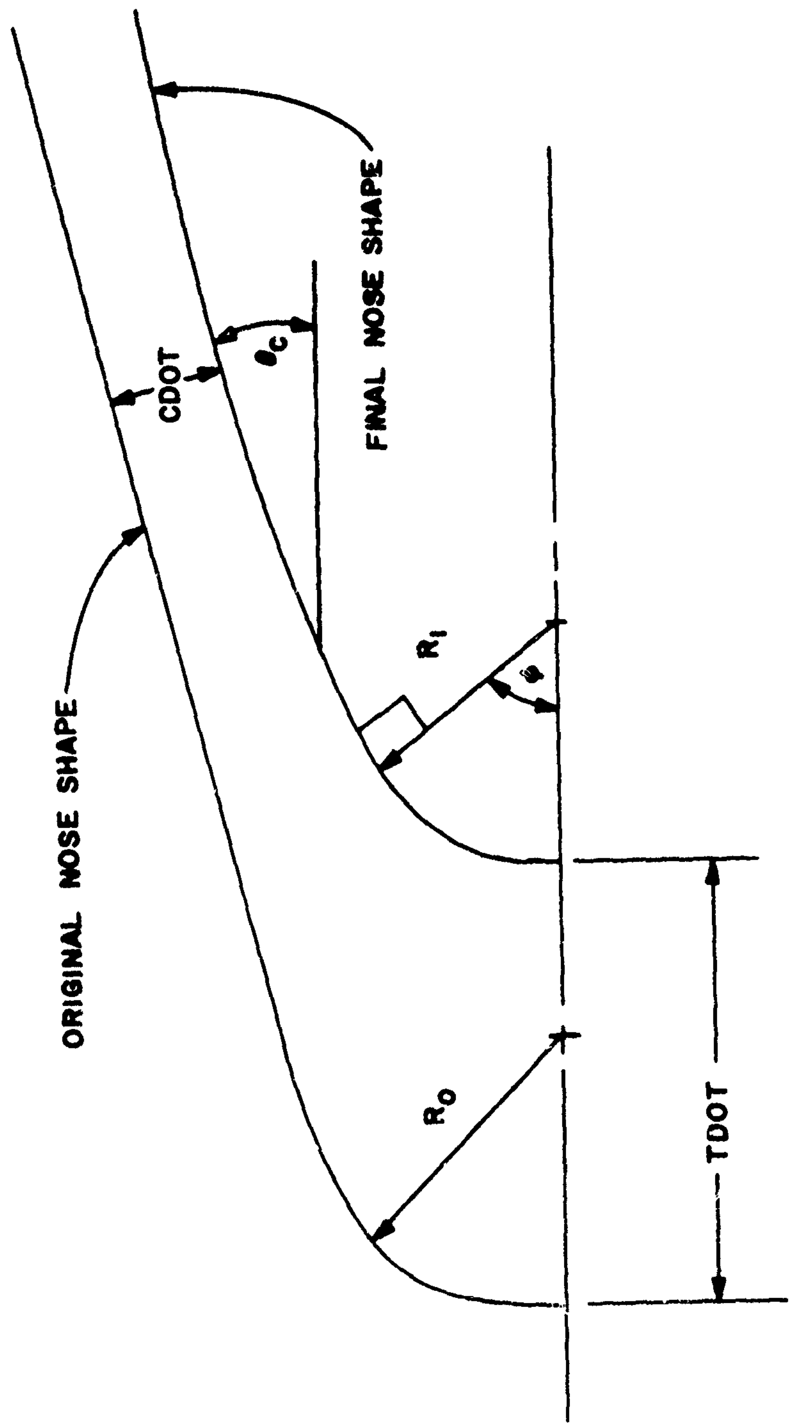

Figure 5. Vehicle Nose-Shape Change

TDOT = instantaneous stagnation point recession rate - ft/sec

CDOT = instantaneous cone recession rate - ft/sec

SECTION IV

BOUNDARY LAYER TRANSITION

The problem of transition from laminar to turbulent boundary layer flow has always been a troublesome one for the aeronautical engineer. The standard approach has usually been to design conservatively, that is, for turbulent flow. In general, the transition Reynolds number has been found to depend upon the local Mach number, which has been observed in the analysis of boundary layer transition on a series of flight vehicles. Transition on blunt spherical nose vehicles with low edge of boundary layer Mach numbers appears to occur at Reynolds number of 1.5×10^5, while on sharp bodies where the edge of the boundary layer Mach numbers approach 10, Reynolds numbers as high as 2.0×10^6 have been observed prior to transition. Thus, for untested vehicle configurations, it is necessary to investigate the relationship of the Mach number and the Reynolds number in both the high and low Mach number regions. It should be noted that flight data on sharp bodies indicates that, generally, transition does not occur instantaneously over the entire vehicle so that it may travel several thousand feet between the onset of transition and the establishment of a fully turbulent boundary layer. These criteria have been summarized by Hecht in reference 8.

The approach of this report is to apply the sharp and blunt body transition Reybolds numbers simultaneously. Therefore, the sharp body criterion is described by the expression

$$Re_{tran} = 2.0 \times 10^6$$

where the Reynolds number is that from a wetted length of one foot to the extreme aft end of a conical vehicle.

The blunt body criterion is applied when either of the following two Reynolds numbers are reached:

$Re_{tran} = 1.5 \times 10^5$ on the spherical nose

$Re_{tran} = 5.0 \times 10^5$ on the conical portion aft of the spherical nose for a wetted length of five times the nose radius

The above criteria has been found to correlate with experimental data.

APPENDIX I

HEATAB Program Listing

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LIST OF SUBROUTINES*

Subroutine	Computes	Versus
ALTUDE	Alt, Altitude of Vehicle	Time
CCPP	CC, Char Specific Heat of Lamina K of Ablator	TW(K)
CTCPC	CT, Char Thermal Conductivity of Lamina K of Ablator	TW(K)
DENS	Rho, Density of Air	Alt
GASE	GE, Ablative Gas Emissivity	TG
GASTC	GTC, Ablative Gas Thermal Conductivity	
GCPB	GCP, Ablative Gas Specific Heat	P
PRESS	PE, Atmospheric Pressure	Alt
QVST	Q, Dynamic Pressure	Time
SPCM	SPC, Cone Surface Pressure Coefficient	AMACH
TCAT	TCA, Thermal Conductivity of Air	TR
TEMPA	Temp, Ambient Temperature	Alt
VCPPC	VC, Virgin Specific Heat of Lamina K of Ablator	TW(K)
VELOC	Vel, Velocity of Vehicle	Time
VISCO	Vis, Viscosity of Ambient Air	Alt
VISCOT	VISG, Ablative Gas Viscosity	TR
VSD	VS, Velocity of Sound	Alt
VTCPC	VT, Virgin Thermal Conductivity of Lamina K of Ablator	TW(K)

*This listing of subroutines common for HEATAB and STAGG.

LIST OF SYMBOLS FOR HEATAB

ACP(K)	Specific heat of ablator (char or virgin), BTU/lb - °R
AJ	778.184, Joule's constant
AKL1 AKL2	Ablator constants for mass loss. Can be interpreted as the intercept and slope respectively on an effective heat of ablation versus enthalpy difference plot for laminar flow.
AKT1 AKT2	Same as above, except for turbulent flow
ALPG	Absorptivity of ablative gas
ALT	Altitude of vehicle, ft
AMACH	Mach number of vehicle
ANR	Computed Reynolds number
ARHO(K)	Density of ablator at lamina K (char or virgin), lbs/ft^3
ATC(K)	Thermal conductivity of ablator at lamina K (char or virgin), BTU/ft-sec-°R
CPA	Specific heat of air, BTU/lb-°R
DE(K)	Instantaneous lamina thickness, ft
DEL(K)	Original lamina thickness, ft
DELT	Time step, sec
DMD	Diffusion controlled oxidation mass loss
DTR	Dynamic temperature rise, °R
E	2.7183
G	Gravitational acceleration, ft/sec^2
GCP	Ablation gas specific heat, BTU/lb-°R
GTC	Ablation gas thermal conductivity, BTU/ft-°R-sec
GVIS	Boundary layer air viscosity, $lb\text{-}sec/ft^2$
HE	Convective heat transfer coefficient, BTU/ft^2-sec- °R
IND(K) = 0	Lamina K of ablator is virgin
IND(K) = 1	Lamina K of ablator is char
JIND = 0	Outermost lamina not ablating
JIND = 1	Outermost lamina is ablating
NAL	Number of ablative laminas
NP1	Number which refers to bond lamina
NP2	Number which refers to aluminum skin
P	Boundary layer pressure, Atmospheric
PE	Ambient pressure, psi

PBL	Boundary layer edge pressure, psi
PR	Prandtl number
PXE	Dummy variable
Q	Dynamic pressure, psf
QDOTC	Convective heat rate, BTU/ft^2-sec
QDOTR	Hot gas radiation heat rate, BTU/ft^2-sec
RE	Transition Reynolds number
RF	Recovery factor
RHO	Ambient density of air, lb-sec^2/ft^3
RHOC	Char ablator density, lb/ft^3
RHOV	Virgin ablator density, lb/ft^3
S	Instantaneous ablator wall recession rate
SDOT	Total ablator wall recession, ft
SIGMA	Stephan-Boltzmann constant
SPC	Cone surface pressure coefficient
TAW	Adiabatic wall temperature, °R
TCA	Thermal conductivity of air, BTU/ft-°R-sec
TEM	Initial temperature of laminas, °R
TEMP	Ambient temperature, °R
TG	Ablation gas temperature, °R
TIME	Elapsed time, sec
TM	Total mass from ablation
TMDOT	Instantaneous mass loss rate
TMELT	Temperature at which ablation starts, °R
TR	Reference temperature, °R
TW(K)	Temperature of lamina K, °R
VEL	Tangential velocity of vehicle, ft/sec
VIS	Viscosity of ambient air, lb-sec/ft^2
VISG	Ablative gas viscosity, lb-sec/ft^2
VS	Velocity of sound, ft/sec
X	Wetted length from nose to station on cone, ft
WT	Instantaneous weight loss rate

```
      PROGRAM HEATAB(INPUT,OUTPUT)
C     AERODYNAMIC HEATING ON CONE
      DIMENSION TW(50),IND(50),ATC(50),ACP(50),ARHO(50),DEL(50),DE(50)
      READ 1,AJ,AKL1,AKL2,AKT1,AKT2,G,GVIS,SIGMA,NAL,NP1,NP2,E,TMELT,
     1ARHO(NP1),ARHO(NP2),ATC(NP1),ATC(NP2),ACP(NP1),ACP(NP2),DEL(NP1),
     2DEL(NP2),DE(NP1),DE(NP2),DELT,RE,VEL,TEMP,CPA,RHOV,
     3RHOC,TEM,TOL,X
1     FORMAT(     AS       NECESSARY     )
      DO 2 N=1,NP2
      TW(N)=TEM
2     IND(N)=0
      DO 3 N=1,NAL
      DEL(N)=TOL
3     DE(N)=TOL
      SDOT=0.
      JIND=0
      TIME=-DELT
      TAW=TEMP
      PRINT 4
4     FORMAT(          HEADINGS AS NECESSARY      )
100   TIME=TIME+DELT
      DO 6 N=1,NAL
      AN=N
      IF (AN*DEL(1) - SDOT)  6,8,8
6     CONTINUE
      PRINT 7
7     FORMAT(10H  OVERHEAT/)
      GO TO 200
8     K=N
      TR=TEMP+.58*(TW(K)-TEMP)+.19*(TAW-TEMP)
      CALL ALTUDE(ALT,TIME)
      CALL VSD(VS,ALT)
      CALL VELOC(VEL,TIME)
      AMACH=VEL/VS
      CALL TEMPA(TEMP,ALT)
      CALL RHOF(RHO,ALT)
      CALL VISCO(VIS,ALT)
      CALL TCAT(TCA,TR)
      CALL VISCOT(VISG,TR)
      CALL SPCM(SPC,AMACH)
      CALL QVST(Q,TIME)
      CALL PRESS(PE,ALT)
      PBL=SPC*Q+PE
      P=PBL/2116.2
      IF(JIND.EQ.0)GO TO 9
      CALL GCPB(GCP,P)
      CALL GASTC(GTC,GCP)
      PR=GCP*GVIS/GTC
      GO TO 10
9     PR=CPA*VISG/TCA
10    ANR=VEL*X*RHO/VIS
      IF(ANR.GT.RE)GO TO 12
11    RF=PR**.5
      HE=.575*TCA/X*PR**.33*ANR**.5
      GO TO 13
12    RF=PR**.33
```

```
      HE=.0296*TCA/X*PR**.33*ANR**.8
   13 DTR=VEL**2./(2.*G*AJ*CPA)
      TAW=TEMP+RF*DTR
      TG=TEMP+DTR
      CALL GASF(GE,TG)
      ALPG=.022*(TG/TMELT)**.45
      QDOTC=HE*(TAW-TW(K))*DELT
   14 IF(IND(K).EQ.1)GO TO 17
      IF(TW(K).GE.TMELT)GO TO 17
   15 TWK=TW(K)
      CALL VTCPC(VT,TWK)
      CALL VCPPC(VC,TWK)
      ATC(K)=VT
      ACP(K)=VC
      ARHO(K)=RHOV
      IF(K.EQ.1)GO TO 18
      TW(K)=TW(K)+DELT*(ATC(K-1)/(ARHO(K-1)*ACP(K-1)*DE (K-1)**2)*
     1(TW(K-1)-TW(K))-ATC(K)/(ARHO(K)*ACP(K)*DE (K)**2)*(TW(K)-TW(K+1)))
      IF(TW(K).LT.TMELT)GO TO 31
   16 TW(K)=TMELT-1.
      GO TO 31
   17 TWK=TW(K)
      CALL CTCPC(CT,TWK)
      CALL CCPP(CC,TWK)
      ACP(K)=CC
      ATC(K)=CT
      ARHO(K)=RHOC
      IND(K)=1
   18 TW(K)=TW(K)+DELT/(ACP(K)*ARHO(K)*DE (K))*(HE*(TAW-TW(K))-
     1ATC(K)/DE (K)*(TW(K)-TW(K+1)))
   19 IF(TW(K).GE.TMELT)GO TO 21
   20 JIND = 0
      GO TO 31
   21 TW(K)=TMELT
      IND(K)=1
      JIND=1
      CALL GCPB(GCP,P)
      QDOTR=SIGMA*(GE*TG**4-ALPG*TMELT**4)*DELT
      IF(QDOTR)22,22,23
   22 QDOTR=0.
   23 IF(ANR.GT.RF)GO TO 25
   24 DMD=(QDOTC+QDOTR)/(AKL1+AKL2*(GCP*TAW-CPA*TMELT))
      GO TO 26
   25 DMD=(QDOTC+QDOTR)/(AKT1+AKT2*(GCP*TAW-CPA*TMELT))
   26 PXE=11.05E+04/TMELT
      TMDOT = DMD*(1. + 2.64E+09/(PBL**.67*E**PXE))
      TM=TM+TMDOT
      SDOT=TM/RHOV
      S=TMDOT/RHOV
      WT=3.1416*2.*R**2*S*RHOV
      DO 29 N=1,NAL
      BN=N
      IF (BN*DEL(1) - SDOT) 29,30,30
   29 CONTINUE
      PRINT 7
      GO TO 200
   30 DE(N)=DEL(N)-(SDOT-(N-1)*DEL(1))
```

```
      IND(N)=1
      IF(N.EQ.1)GO TO 31
      DE(N-1)=0.0
31    K=K+1
      IF(K.LE.NAL)GO TO 14
      TW(K)=TW(K)+DELT*(ATC(K-1)/(ARHO(K-1)*ACP(K-1)*DE(K-1)**2)*(TW(K
     1-1)-TW(K))-ATC(K)/(ARHO(K)*ACP(K)*DEL(K)**2)*(TW(K)-TW(K+1)))
      K=K+1
      TW(K)=TW(K)+DELT*(ATC(K-1)/(ARHO(K-1)*ACP(K-1)*DEL(K-1)**2)*
     1(TW(K-1)-TW(K)))
      PRINT 5,TIME,ALT,VEL,ANR,TAW,TEMP,HE,QDOTC,WT,TM,TG,SDOT,
     1(TW(N),N=1,NP2)
5     FORMAT(    AS NECESSARY    )
      IF(ALT)200,200,100
200   CONTINUE
      END
```

APPENDIX II

STAGG Program Listing

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LIST OF SYMBOLS FOR STAGG

CDOT	Instantaneous cone recession rate, ft/sec
PHI	See figure 5
R	Radius of spherical nose, ft
TCAE	Time cone ablation ends
TCAS	Time cone ablation starts
THETC	Cone half-angle, rad

```
      PROGRAM STAGG(INPUT,OUTPUT)
C     STAGNATION HEATING
      DIMENSION TW(50),IND(50),ATC(50),ACP(50),ARHO(50),DEL(50),DE(50)
      READ 1,AJ,AKL1,AKL2,AKT1,AKT2,G,GVIS,SIGMA,NAL,NP1,NP2,E,TMELT,
     1ARHO(NP1),ARHO(NP2),ATC(NP1),ATC(NP2),ACP(NP1),ACP(NP2),DEL(NP1),
     2DEL(NP2),DE(NP1),DE(NP2),DELT,R,THETC,PHI,RE,VEL,TEMP,CPA,RHOV,
     3RHOC,TCAS,TEM,TOL,TCAF
1     FORMAT(  AS NECESSARY   )
      DO 2 N=1,NP2
      TW(N)=TEM
2     IND(N)=0
      DO 3 N=1,NAL
      DEL(N)=TOL
3     DE(N)=TOL
      CDOT=0.0
      SDOT=0.
      JIND=0
      TIME=-DELT
      X=.01745*R*PHI
      TAW=TEMP
      PRINT 4
4     FORMAT(    HEADINGS   AS   NECESSARY   )
100   TIME=TIME+DELT
      DO 6 N=1,NAL
      AN=N
      IF (AN*DEL(1) - SDOT)  6,8,8
6     CONTINUE
      PRINT 7
7     FORMAT(10H  OVERHEAT/)
      GO TO 200
8     K=N
      TR=TEMP+.58*(TW(K)-TEMP)+.19*(TAW-TEMP)
      CALL ALTUDE(ALT,TIME)
      CALL VSD(VS,ALT)
      CALL VELOC(VEL,TIME)
      AMACH=VEL/VS
      CALL TEMPA(TEMP,ALT)
      CALL RHOF(RHO,ALT)
      CALL VISCO(VIS,ALT)
      CALL TCAT(TCA,TR)
      CALL VISCOT(VISG,TR)
      CALL SPCM(SPC,AMACH)
      CALL QVST(Q,TIME)
      CALL PRESS(PE,ALT)
      PBL=SPC*Q+PE
      P=PBL/2116.2
      IF(JIND.EQ.0)GO TO 9
      CALL GCPB(GCP,P)
      CALL GASTC(GTC,GCP)
      PR=GCP*GVIS/GTC
      GO TO 10
9     PR=CPA*VISG/TCA
10    ANR=VEL*X*RHO/VIS
      IF(ANR.GT.RE)GO TO 12
11    RF=PR**.5
      HF=.778*TCA/X*PR**.33*ANR**.5
      GO TO 13
```

```
12    PF=PR**.33
      HE=.0296*TCA/X*PR**.33*ANR**.8
13    DTR=VEL**2./(2.*G*AJ*CPA)
      TAW=TEMP+RF*DTR
      TG=TEMP+DTR
      CALL GASE(GE,TG)
      ALPG=.022*(TG/TMELT)**.45
      QDOTC=HE*(TAW-TW(K))*DELT
14    IF(IND(K).EQ.1)GO TO 17
      IF(TW(K).GE.TMELT)GO TO 17
15    TWK=TW(K)
      CALL VTCPC(VT,TWK)
      CALL VCPPC(VC,TWK)
      ATC(K)=VT
      ACP(K)=VC
      ARHO(K)=RHOV
      IF(K.EQ.1)GO TO 18
      TW(K)=TW(K)+DELT*(ATC(K-1)/(ARHO(K-1)*ACP(K-1)*DE  (K-1)**2)*
     1(TW(K-1)-TW(K))-ATC(K)/(ARHO(K)*ACP(K)*DE  (K)**2)*(TW(K)-TW(K+1)))
      IF(TW(K).LE.TMELT)GO TO 31
16    TW(K)=TMELT-1.
      GO TO 31
17    TWK=TW(K)
      CALL CTCPC(CT,TWK)
      CALL CCPP(CC,TWK)
      ACP(K)=CC
      ATC(K)=CT
      ARHO(K)=RHOC
      IND(K)=1
18    TW(K)=TW(K)+DELT/(ACP(K)*ARHO(K)*DE  (K))*(HE*(TAW-TW(K))-
     1ATC(K)/DE  (K)*(TW(K)-TW(K+1)))
19    IF(TW(K).GE.TMELT)GO TO 21
20    JIND = 0
      GO TO 31
21    TW(K)=TMELT
      IND(K)=1
      JIND=1
      CALL GCPB(GCP,P)
      QDOTR=SIGMA*(GE*TG**4-ALPG*TMELT**4)*DELT
      IF(QDOTR)22,22 23
22    QDOTR=0.
23    IF(ANR.GT.R            25
24    DMD=(QDOTC+QDOTR)/(AKL1+AKL2*(GCP*TAW-CPA*TMELT))
      GO TO 26
25    DMD=(QDOTC+QDOTR)/(AKT1+AKT2*(GCP*TAW-CPA*TMELT))
26    PXE=11.05E+04/TMELT
      TMDOT = DMD*(1. + 2.64E+09/(PBL**.67*E**PXE))
      TM=TM+TMDOT
      SDOT=TM/RHOV
      S=TMDOT/RHOV
      WT=3.1416*2.*R**2*S*RHOV
      IF(TIME.LT.TCAS .OR. TIME.GT.TCAE)GO TO 28
      READ 27,CDOT
27    FORMAT(F11.5)
28    R=R+1./(1.-SIN(THETC))*(SIN(THETC)*S-CDOT)
      X=.01745*R*PHI
```

```
      DO 29 N=1,NAL
      BN=N
      IF (BN*DEL(1) - SDOT)  29,30,30
29    CONTINUE
      PRINT 7
      GO TO 200
30    DE(N)=DEL(N)-(SDOT-(N-1)*DEL(1))
      IND(N)=1
      IF(N.EQ.1)GO TO 31
      DE(N-1)=0.0
31    K=K+1
      IF(K.LE.NAL)GO TO 14
      TW(K)=TW(K)+DELT*(ATC(K-1)/(ARHO(K-1)*ACP(K-1)*DE(K-1)**2)*(TW(K
     1-1)-TW(K))-ATC(K)/(ARHO(K)*ACP(K)*DEL(K)**2)*(TW(K)-TW(K+1)))
      K=K+1
      TW(K)=TW(K)+DELT*(ATC(K-1)/(ARHO(K-1)*ACP(K-1)*DEL(K-1)**2)*
     1(TW(K-1)-TW(K)))
      PRINT 5,TIME,ALT,VEL,ANR,TAW,TEMP,HE,QDOTC,WT,TM,TG,SDOT,R,
     1(TW(N),N=1,NP2)
5     FORMAT(   AS NECESSARY   )
      IF(ALT)200,200,100
200   CONTINUE
      END
0265
```

APPENDIX III

HEATAB 3 Listing

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HEATAB 3, Version of HEATAB

HEATAB 3, a modification and extension of the basic HEATAB program, calculates the total ablation mass loss rate for a conical reentry vehicle. The body is divided into a number of segments, or stations, and the heating rate at each station is computed. In addition to the input data required in HEATAB, the fore and aft radii and slant lengths of each body segment must be supplied to the computer. This input into the program is identified by the comment statement "Additional Vehicle Data." Computation of the skin temperature profile is identical to the method used in HEATAB, except that this calculation is made for each x-station for each trajectory point.

To compute the total mass loss rate, the following procedure is used. The weight loss rate per unit area is first computed then the instantaneous and total recessions are calculated. Using these numbers and the initial radii and slant length of the particular segment of interest, the mass loss rate per unit area is multiplied by the appropriate surface area to give a local integrated mass loss rate. Summing these local rates over the body results in the total weight loss rate.

As written, the HEATAB 3 output will give, for each time interval, an output of trajectory conditions and body conditions. The trajectory conditions are items such as altitude, velocity, and Mach number. Body conditions listed for each x-station are Reynolds number, weight loss rate per unit area, wall recession, and wall temperature.

LIST OF SYMBOLS, HEATAB 3

TW(I,J)	Layer temperature at lamina I and station J
IND(I,J)	0 = virgin material 1 = char material
JIND(I)	0 = not ablating 1 = ablating
VCP(I,J)	Virgin specific heat
VTC(I,J)	Virgin thermal conductivity
VRHO(I,J)	Virgin density
DEL(I,J)	Original lamina thickness
DE(I,J)	Instantaneous lamina thickness
SDOT	Total recession of wall
XI(J)	Location of x-station, ft
RS(J)	Smaller radius of cone segment for a particular x-station
RL(J)	Larger radius of cone segment for a particular x-station
SL(J)	Slant height at station X
WT(J)	Instantaneous weight loss rate at station X, lb/sec
TM(J)	Total weight flux at station X, lb/ft^2-sec
TMELT	Ablation temperature, °R
RE	Transition Reynolds number
DELT	Time step, sec
TEMP	Ambient temperature at altitude, ALT
TAW	Adiabatic wall temperature, °R
SIGMA	Stephan-Boltzmann constant
GVIS	Ablation gas viscosity
AKL1 AKL2	(See HEATAB Symbol Listing)
AKT1 AKT2	(See HEATAB Symbol Listing)
CHA	Cone half-angle
NOFX	Number of x-stations
TIME	Time, sec
ALT	Altitude, ft
AMACH	Mach number
VELS	Acoustic velocity, ft/sec
RHO	Ambient density, slugs/ft^3

VIS	Ambient viscosity
SPC	Cone surface pressure coefficient
VEL	Velocity, ft/sec
Q	Dynamic pressure lb/ft^2
TCA	Air thermal conductivity
VISG	Air viscosity
PE	Ambient pressure, lb/ft^2
CPA	Specific heat of air
PBL	Boundary layer edge pressure, lb/ft^2
P	Boundary layer pressure, atms
GCP	Ablation gas specific heat
GTC	Ablation gas thermal conductivity
PR	Prandtl number
ANR	Reynolds number
RF	Recovery factor
HE	Convective heat transfer coefficient
DTR	Dynamic temperature rise
TG	Gas temperature
GE	Gas emissivity
ALPG	Absorbtivity at gas
QDOTC	Convective heat flux
TWK	Dummy variable used in subroutines
VT	Dummy variable (virgin thermal conductivity)
VC	Dummy variable (virgin specific heat)
CC	Dummy variable (char specific heat)
CT	Dummy variable (char thermal conductivity)
QDOTR	Hot gas radiation heat flux
DMD	Diffusion controlled oxidation mass loss
PXE	Dummy variable in TMDOT equation
TMDOT	Mass loss rates in sublimation region
CDOT	instantaneous recession
WDOT	Integrated weight loss rate, lb/sec

```
JDY0001.6.100.50000.YOUNG.5791.WLDE.2241.
RUN(,75000,,,,,30000'
HEATAB3.
.
      PROGRAM HEATAB3(INPUT,OUTPUT)
C     AERODYNAMIC HEATING FOR R/V
C     THIS MODIFICATION OF HEATAB GIVES THE ABLATION MASS LOSS RATE
C     FOR A RE-ENTERING BODY.
      DIMENSION TW(6,10),IND(6,10),JIND(10),VCP(6,10),VTC(6,10),VRHO(6,
     110),DEL(6,10),DE(6,10),SDOT(10),XI(10),RS(10),RL(10),SL(10),WT(10)
     2,TM(10)
C     CONSTANTS DEFINED
      PI=3.14159
      E=2.718
      TMELT =6760.
      RE = 1.E+7
      DELT=.05
      TEMP=298.2
      TAW=TEMP
      G = 32.169
      AJ = 778.
      SIGMA = 4.8E-13
      GVIS = 4.429E-5
      AKL1 = 5370.
      AKT1 = 4240.
      AKL2 = 5.37
      AKT2 = 5.77
      PRINT 501
  501 FORMAT(1H1)
C     IDENTIFICATION CARD
      READ 502
  502 FORMAT(80H
     1                                                                  )
      PRINT 502
C     INPUT - CONE HALF ANGLE, NUMBER OF X-STATIONS, X-STATIONS
      READ 503, CHA,NOFX,(XI(I), I=1,NOFX)
  503 FORMAT(F10.4,5X,I5,5F10.4/8F10.4)
      PRINT 504,CHA,NOFX,(XI(I),I=1,NOFX)
  504 FORMAT(2(,18HCONE HALF ANGLE = ,F8.2,5X,23HNUMBER OF X-STATIONS =
     1,I5,/,5X,10HX-STATIONS,/,(5X,F10.3))
      DO 1 J = 1,NOFX
      JIND(J) = 0
      VCP(5,J) = .315
      VCP(6,J) = .208
      VTC(5,J)=.74E-04
      VTC(6,J) = .03694
      VRHO(5,J) = 91.7
      VRHO(6,J) = 169.
      DO 1 I = 1,6
      TW(I,J) = 544.
    1 IND(I,J) = 0
C     ADDITIONAL VEHICLE DATA
      READ 505,(RL(J),J=1,NOFX)
      READ 505,(RS(J),J=1,NOFX)
      READ 505,(SL(J),J=1,NOFX)
  505 FORMAT(8F10.5)
      DO 95 I = 1,3
```

```
      DO 95 J=1,NOFX
      DEL(I,J) = .00833
   95 DE (I,J) = .00833
      DO 96 I = 1,NOFX
      DEL(4,I) = .00941
       DE (4,I) = .00941
      DEL(5,I) = .00333
      DE (5,I) = .00333
      DEL(6,I) = .005
   96 DE (6,I) = .005
C     INPUT - TIME, ALTITUDE, AND MACH NUMBER FROM TRAJECTORY
  500 READ 506,TIME,ALT,AMACH
  506 FORMAT(3F10.2)
      IF (TIME-20.50) 1000,1000,403
 1000 CALL VELSF(VELS,ALT)
      CALL TEMPA(TEMP,ALT)
      CALL RHOF(RHO,ALT)
      CALL VISCO(VIS,ALT)
      CALL SPCM(SPC,AMACH)
      VEL=VELS*AMACH
      Q = .5*RHO*VEL**2
  517 PRINT 507, TIME ,ALT, VEL, AMACH, Q
  507 FORMAT(/,2X,7HTIME = ,F7.2,5X,11HALTITUDE = ,F10.2,5X,11HVELOCITY
     1= ,F9.2,5X,10HMACH NO = ,F5.2,5X,19HDYNAMIC PRESSURE = ,E12.6,/,
     22X,7HSTATION,6X,15HREYNOLDS NUMBER,5X,26HWEIGHT LOSS RATE (LBS/SEC
     3),5X,15HTOTAL RECESSION,5X,16HWALL TEMPERATURE)
C     CALCULATE FOR EACH X-STATION
      DO 401 LEN = 1,NOFX
      X = XI(LEN)
      IF (SDOT(LEN)-.00833) 6,7,7
6     K=1
      GO TO 15
    7 IF(SDOT(LEN) - .01666)8,9,9
8     K=2
      IND(K,LEN) = 1
      GO TO 15
    9 IF(SDOT(LEN) - .02499) 10,11,11
10    K=3
      IND(K,LEN) = 1
      GO TO 15
   11 IF(SDOT(LEN) - .0341) 12,13,13
12    K=4
      IND(K,LEN) = 1
      GO TO 15
13    PRINT 14
14    FORMAT(*      OVERHEAT*)
      GO TO 403
   15 TR=TEMP+.58*(TW(K,LEN)-TEMP)+.19*(TAW-TEMP)
      CALL TCAT(TCA,TR)
      CALL VISCOT(VISG,TR)
      PE=2116.2*E**(-4.25509E-05*ALT)
      CPA=.2395
      PBL=SPC*Q+PE
      P=PBL/2116.2
      IF(JIND(LEN).EQ.0)GO TO 16
      CALL GCPP(GCP,P)
      GTC=4.429E-05*(GCP+.297)
```

```
      PR=GCP*GVIS/GTC
      GO TO 17
16    PR=CPA*VISG/TCA
17    ANR=VEL*X*RHO/VIS
      IF(ANR-RE)18,18,19
18    RF=PR**.5
      HE=.575*TCA/X*PR**.33*ANR**.5
      GO TO 20
19    RF=PR**.33
      HE=.0296*TCA/X*PR**.33*ANR**.8
20    DTR=VEL**2./(2.*G*AJ*CPA)
      TAW=TEMP+RF*DTR
      TG=TEMP+DTR
      IF(TG-8500.)22,21,21
21    GE=.02169
      GO TO 23
22    GE=.085*E**(-.61144E-03*TG)
23    ALPG=.08*(TG/TMELT)**.45
      QDOTC = HE*(TAW-TW(K,LEN))*DELT
      IF(IND(K,LEN).EQ.1)GO TO 26
   24 IF(TW(K,LEN)-TMELT)25,26,26
   25 TWK=TW(K,LEN)
      CALL VTCPC(VT,TWK)
      CALL VCPPC(VC,TWK)
      VTC(K,LEN)=VT
      VCP(K,LEN) = VC
      VRHO(K,LEN)=90.4
      IF(K.EQ.1)GO TO 27
      TW(K,LEN)=TW(K,LEN)+DELT*(VTC(K-1,LEN)/(VRHO(K-1,LEN)*VCP(K-1,LEN)
     1*DE(K-1,LEN)**2)*(TW(K-1,LEN)-TW(K,LEN))-VTC(K,LEN)/ (VRHO(K,LEN)
     2*VCP(K,LEN)*DE(K,LEN)**2)*(TW(K,LEN)- TW(K+1,LEN)))
   50 IF(TW(K,LEN)-TMELT)36,51,51
   51 TW(K,LEN)=TMELT-1.
      GO TO 36
   26 TWK = TW(K,LEN)
      CALL CTCPC(CT,TWK)
      CALL CCPP(CC,TWK)
      VCP(K,LEN)=CC
      VTC(K,LEN)=CT
      VRHO(K,LEN)=74.
   27 TW(K,LEN)=TW(K,LEN)+DELT/(VCP(K,LEN)*VRHO(K,LEN)*DE(K,LEN))*(HE*(T
     1AW-TW(K,LEN))-VTC(K,LEN)/DE(K,LEN)*(TW(K,LEN)-TW(K+1,LEN)))
   28 IF(TW(K,LEN)-TMELT)72,29,29
   72 JIND(LEN) = 0
      GO TO 36
   29 TW(K,LEN)=TMELT
      IND(K,LEN)=1
      JIND(LEN)=1
      CALLGCPP(GCP,P)
      QDOTR=SIGMA*(GE*TG**4-ALPG*TMELT**4)*DELT
      IF(QDOTR)31,31,32
31    QDOTR=0.
32    IF(ANR-RE)33,33,34
33    DMD=(QDOTC+QDOTR)/(AKL1+AKL2*(GCP*TAW-CPA*TMELT))
      GO TO 35
34    DMD=(QDOTC+QDOTR)/(AKT1+AKT2*(GCP*TAW-CPA*TMELT))
35    PXE-11.05E+04/TMELT
```

```
      TMDOT = DMD*(1. + 2.64E+09/(PBL**.67*F**PXF ))
      TM(LEN)=TM(LEN)+TMDOT
      SDOT(LEN)=TM(LEN)/74.
      CDOT=TMDOT/74.
      WT(LEN)=PI*(PL(LEN)+PS(LEN)-2.*SDOT(LEN))*CDOT*90.4* SL(LEN)
      JIND(LEN)=1
      IF(SDOT(LEN)-.00833)53,54,54
   54 IF(SDOT(LEN)-.01666)55,56,56
   56 IF(SDOT(LEN)-.02499)57,58,58
   58 DE(4,LEN)=DEL(4,LEN)-(SDOT(LEN)-3.*DEL(1,LEN))
      GO TO 36
   57 DE(3,LEN)=DEL(3,LEN)-(SDOT(LEN)-2.*DEL(1,LEN) )
      GO TO 36
   55 DE(2,LEN)=DEL(2,LEN)-(SDOT(LEN)-DEL(1,LEN))
      GO TO 36
   53 DE(1,LEN)=DEL(1,LEN)-SDOT(LEN)
36    K=K+1
      IF(K.GT.4)GO TO 37
      GO TO 24
   37 TW(5,LEN)=TW(5,LEN)+DELT*(VTC(4,LEN)/(VRHO(4,LEN)*VCP(4,LEN)*DE(4,
     1LEN)**2)*(TW(4,LEN)-TW(5,LEN))-VTC(5,LEN)/(VRHO(5,LEN)*VCP(5,LEN)*
     2DEL(5,LEN)**2)*(TW(5,LEN)-TW(6,LEN)))
      TW(6,LEN)=TW(6,LEN)+DELT*(VTC(5,LEN)/(VRHO(5,LEN)*VCP(5,LEN)*DEL(5
     1,LEN)**2)-(TW(5,LEN)-TW(6,LEN)))
   41 PRINT 509,X,ANP,WT(LEN),SDOT(LEN),TW(1,LEN)
  509 FORMAT(F10.3,5X,F14.8,14X,F9.4,20X,F7.5,10X,F6.0)
  401 CONTINUE
      WDOT = 0.0
C     CALCULATE TOTAL WEIGHT LOSS RATE
      DO 402  LL = 1,NOFX
      WDOT = WDOT + WT(LL)
  402 CONTINUE
      PRINT 508,ALT,VEL,WDOT
  508 FORMAT(2X,19HFOR AN ALTITUDE OF ,F10.2,23HFEET AND A VELOCITY OF ,
     1F8.2,32HFT/SEC, THE WEIGHT LOSS RATE IS ,F6.3,8HLBS/SEC.)
      GO TO 500
  403 CONTINUE
      END
```

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13. ABSTRACT

An Aerodynamic Heating and Ablation Computer Program (HEATAB) is presented to establish a means by which heat transfer problems may be solved with minimum effort. This program computes the boundary layer conditions, time-temperature distribution in a body, the ablation recession rate, and weight loss. The program was written in Fortran IV for the CDC 6600 computer.

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